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Impact of dynamic aspects on economics of fuel cell based micro co-generation in low carbon futures

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A R T I C L E I N F O

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A B S T R A C T

This article evaluates the impact of a range of dynamic performance parameters on the techno-economics of fuel cell based micro co-generation. The main novelties in methodology are: (1) Analysis in the context of future power system decarbonisation, (2) Use of the Long Run Marginal Cost of electricity, (3) Combination of the above with dynamic aspects such as start-up cost, ramping limit, turn down ratio, minimum up time and minimum down time and (4) Identification of sensitive parameters for future research. To this end it combines a national level energy systems model with an individual heating system model. A case study of the United Kingdom is considered for the year 2035. Economic viability of fuel cell based micro co-generation hinges upon the use of an optimized control strategy. With such a control strategy, a hot start-up approach offers much greater economic potential than a cold start-up approach. The best case ratio of maximum allowable hot standby power to the nominal value is 4.2 while the ratio for cold start is only 1.1. Combinations involving low ramping limits less than 70 W/min and limited turn down ratios above 35% need to be avoided as they seriously hinder economic performance.

1. Introduction

Energy systems across the world are faced with significant challenges as they are faced with the prospect of potentially severe consequences due climate change [1]. The energy sector has to contend with ensuring affordability, reliability and sustainability in a continuously evolving landscape [2]. This means the system now has to incorporate increasing contributions from new sources, namely low carbon and distributed energy resources, that complement or eventually replace conventional centralised energy provision [3].

Against this backdrop, fuel cell based micro co-generation is a promising technology that has several advantages. Their high overall efficiencies allow them to considerably reduce primary energy consumption, and transmission losses are enabled via co-locating the system with the demand [4]. They can run on natural gas and thereby capitalise on existing supply network infrastructure. By providing both electricity and heat they help offset the import of electricity and hence reduce associated energy cost. Their high electrical efficiencies and low heat to power ratios also make them well suited for the demand profiles encountered in the domestic sector [5]. As large scale uptake of fuel cell based micro co-generation can also help avoid reinforcement of generation capacity, this technology could potentially play a significant role in energy systems of the future [6]. Hence there is a pressing need for tools that can assess the viability of this technology in energy systems of the future.

The rest of this article is structured as follows: The next section presents the background context to this problem, reviewing the current status and studies to date. This is followed by the methodology applied herein to characterise fuel cell based micro co-generation and the possible energy systems it could operate within. The results are then presented and discussed, leading to conclusions.

1.1. Previous literature

Previous literature is assessed by analysing whether the modelling approach suits the objective of the study. This article incorporates dynamic aspects of fuel cells into the operation of the micro cogeneration system in a low carbon future. It aims to evaluate two factors: firstly whether such dynamic aspects have an

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impact on the economics of such systems and secondly to identify which aspects of design impact the economics the most. Hence the modelling approach selected should be able to provide recommendations regarding aspects of fuel cell based micro cogeneration that should be prioritized in the future.

1.1.1. Simulation based models

In simulation based approaches emphasis is laid on modelling responses to parameters that undergo change, for example, power or heat demand, temperature variations within a building, rate of heat exchange etc. The model steps through time and simulates how the components react to the changes in circumstances. The operating strategies are predefined and only serve as inputs to the model.

One type of simulation model makes use of subroutines that can characterise operation by using simple arithmetic operations. This can be done since the model assumes a constant output either at maximum capacity [7] or with the addition of ON/OFF logic [8]. In other cases the output follows either thermal or electric demand [9,10]. The techno-economic results obtained are similar to first order calculations usually done in spreadsheets for off-design evaluation of fuel cell based micro cogeneration.

Another group of models calculate demand profiles from external parameters such as climatic conditions, building materials, building designs and occupancy patterns. In case the fuel cell micro cogeneration unit is operated in load following mode, equipment specifications are necessary for part load efficiencies. These models can represent thermal interactions by using either lumped thermal capacitances [11], or commercial building simulations packages such as eQUEST [12], DesignBuilder [13] or TRNSYS [14]. Sophisticated models describing the physics, chemistry and electrochemistry also exist [15].

The main drawback of this approach is inefficiency. This is so because it does not involve strategic planning. Merely following the load can lead to problems while incorporating dynamic characteristics. The unit could be sensitive to load fluctuations and switch on the fuel cell for a brief blip in demand but be forced to remain active in the following periods which have no demand due to minimum up time specifications. In a similar fashion, the model could shut the unit down because the current period has no demand but be forced to remain inactive due to minimum down time specifications and thus miss out on energy savings when demand increases. Since they do not consider operation beyond just the current period, they cannot describe the operation of thermal energy storage units either.

It can be argued that the constant output capacity can be designed such that it serves the base load or minimum load that the system serves at all points of time. While this may be true for large heat networks and community based cogeneration units, residential household demand can dip to zero and remain there for sustained periods of time. During this time the micro cogeneration unit is dumping heat, wasting fuel. It is also losing a significant amount of money if the electricity export tariff is not large enough to improve economics.

Another limitation is that they are better suited for well-developed and mature technologies whose characteristics are already well known. As fuel cells are still considered to be an emerging technology, we need tools that can assess the best way to design and operate a future system rather than a more detailed analysis of existing configurations.

1.1.2. Design optimization

Optimization with respect to fuel cell based micro cogeneration very often refers to the selection of a static design operating point. These operating conditions either minimise energy consumption or maximize efficiency. Naturally it follows that all the components of the fuel cell micro cogeneration unit need to be described in such models. This means that detailed models of the balance of plant are also necessary. Components described can include the fuel processor, shift reactor, reformer, blower, pre-heater, heat exchangers and burner.

Gandiglio et al. [16] make use of a method known as pinch analysis for design optimization. Pinch analysis is commonly used to optimize heat exchanger networks for a plant or process. This involves accounting for hot/cold streams and heat sources. The pinch point method specifies parameters such as the ideal temperature settings and network configurations for the micro cogeneration unit. Xie et al. [17] make use of energy-exergy balances to support their analysis. Analysis separates useful streams such electricity and hot water from streams that are not useful such as flue gases and condensate from the water separator. A process flow simulator is used to support the analysis. The effect of system parameters such as steam to carbon ratio, air to carbon ratio, hydrogen utilization efficiency on system performance are also evaluated. Barelli et al. [18] analyse a similar concept based on energy-exergy analysis and process flow simulators. It involves the soft linking of electrochemical phenomena represented in FORTRAN with the process flow phenomena in AspenPlus [19]. This is done since AspenPlus does not support electrochemical reactions. Modelling the polarization curve which is a result of the electrochemical portion of the model is of utmost importance while calculating the output power from the micro cogeneration unit. Design analysis can also differ in the type of models involved. The simplest methods use zero-dimensional models [18] with black box representations where the focus is on mapping input and output quantities. When geometry is to be taken into account, one-dimensional [20] and two-dimensional [21] models are used.

Fuel cell models can also be combined with evolutionary programming to determine optimal operating points [22]. Here empirical relations from experimental data are used to represent the equipment for faster simulation. This allows for a large number of model runs which are necessary to prevent the algorithm from settling for a local maxima instead of the global maxima.

Design optimization focuses on the variation of operating parameters to select a static set-point. Such set points are meant to be conducive for efficient long term operation without interruption. As mentioned earlier, the demand profiles encountered in a residential household do not have a minimum base load value. Hence, the static operation is likely to lead to inefficient operation.

Another limitation is that they provide very little information on the gaps in existing technology. This article deals with the change in performance in scenarios where the design parameters themselves are subject to change. Design optimization is rooted in technology rich descriptions of current units and does not provide room for changes that could be encountered in the future.

1.1.3. Optimal operation models

This approach involves the calculation of the best possible operating strategies through the use of optimization solvers. This is different from the previous approach which does not allow the set point to deviate from an optimal design point. In general, such models consist of an objective which minimises cost, energy or emissions and constraints on capacity and feasible operating envelope of the equipment.

The work of Wakui et al. [23] focuses on the situation in Japan and hence has been influenced by the prevailing policy conditions. The export of electricity back to the grid is not allowed in this country. Hence, micro cogeneration systems had to find alternative solutions to handle surplus electricity. One approach is to use the battery storage in plug-in hybrid electric vehicles [23]. This